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QUANDARIES DURING NUMERICAL ANALYSIS ON SHAPE MEMORY PRODUCT

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ABSTRACT

Shape memory alloy is a portion of smart materials. These materials have exclusive property of super elasticity / pseudo elasticity which helps in recovery of shape and strains result in resuming its structural property even from state of plastic deformation. Scientific study on these materials indulges to have growth in medical, aerospace and automotive industrial application. Substantial amount of research is available in the literature to study the properties of these materials with different parameters such as processing and compositions based. However, modeling of these parameters was never cited in the literature, hence motivation for the present work emphasizes to model these parameters as an adjustable coefficients that can be used to perform numerical analysis. The novelty of present work addresses one of important phenomena "strain recovery" and proposes an analytical model which extends the modeling of shape recovery.

KEYWORDS: Shape Memory Alloy (SMA), Nitinol, Shape Memory Actuator & Phase Diagram

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Original Article

1. INTRODUCTION

1.1 Summary

Shape memory alloys (SMAs) are resided under smart materials which are grouped as having different properties when compared to classic material. These materials received significant attention due to their captivating property called as shape memory effect (SME) [1]. As a result, these materials later found to be compatible to biomedical applications because of their low transition temperatures, corrosion resistance and relatively good strength with enough bio-sensible [2]. The magnitude to any material is achieved when its ability of resuming its induced properties such as strain which these materials poses in terms of super elasticity or pseudo elasticity [3] which motivate to make them amenable to aerospace and automotive applications. There are different materials with different compositions exhibiting SME, but only Nickel and Titanium received significant attention due to superior super elasticity range among the available SMAs. Our work is based on the properties of Nitinol (Nickel-Titanium) as referred its importance in structural, thermal & magnetic controllability [4]. In this context there is need for development of a compliant constitutive model which envelopes the important properties associated with SME. Hence the present work is a preliminary work to develop a constitutive model which could be compatible for numerical analysis of SMA.

1.2 Shape Memory Effect (SME)

Nitinol stands for Nickel and Titanium discovery at Naval Ordinance Laboratory (NOL), the origin of this combination took place in 1968 at NOL accidentally during the search for non-ferrous materials that could be used

as tools for dismantling magnetic mines [21] and later the year, properties of Nitinol has been discovered and reported in New York Times[The alloy that remembers]. 1980's witnessed the Nitinol SMA as one of the most amenable material which is highly compatible to biomedical applications. The biomedical field explored the applications of these SMA's to memory clip for intracranial aneurysm surgery [22], catheters and cannula [23], Vascular Surgery [24] and Orthopedics [25] and etc. But, limited applications to the Engineering industries have been extracted because of its inadequate research in understanding the application theme.

2. LITERATURE REVIEW

To ascertain the concept of free energy, an enhanced model is earmarked already on the basis of stress-strain curves and latent heat of phase transition with shear strain **E** by [5] which is well known for Falk's Model. The only drawback Falk's model account for is, constraining the martensite variants during phase transition by Schmids law [6]. Jurgen Sprekels [7] proposed a similar model to [5] for a one dimensional constitutive model using non-convex potentials which particularly connects with B2-M phase transitions. The free energy F is defined in Ginzburg-Landau form. But the paper remarked with results concerning the order of convergence which is one of the assignment that will be addressed in the present work. A robust integration algorithm for super elastic model will be used in the current context; an impressive work in lieu of this is presented in [8]. The following constitutive relations are used to perform the numerical simulations which are derived from [8].

From Cauchy-Borne Hypothesis, the deformation gradient is given by

$$F = F^e F^{tr} \tag{1}$$

Where F^e the elastic is part and F^{tr} is the phase transition part.

And the Kirchhoff stress is given by

$$\tau = p1 + t \tag{2}$$

Where 1 is the second order identity tensor, *p* is the pressure, defined as $p = tr(\tau)/3$

To model the phase transformation from B2-M and M-B2, the author used Drucker-Prager type loading function given in the form

$$F(\tau) = \left\|t\right\| + 3\alpha p \tag{3}$$

Where $\alpha$is a material parameter and ||-|| indicates the Euclidean norm, such that $\left\|t\right\| = [\sum_{A=1}^{3}(t_A)^2]^{\frac{1}{2}}$

The martensitic volume fraction during the phase transformations is given by

$$\dot{\xi}_S = H^{AS}(1-\xi_S)\frac{\dot{F}}{F - R_F^{AS}} \tag{4}$$

As $\dot{\xi}_S = H^{SA}\xi_S\frac{\dot{F}}{F-R_f^{SA}}$

The conditions are given as follows

$$R_f^{AS} = \left[\sigma_f^{AS}\left(\sqrt{\tfrac{2}{3}}+\alpha\right)\right] \quad R_f^{SA} = \left[\sigma_f^{SA}\left(\sqrt{\tfrac{2}{3}}+\alpha\right)\right] \tag{5}$$

Where $\sigma_f^{AS}, \sigma_f^{SA}$, σ_s^{AS} , σ_s^{SA} are material constants. The scalar quantities H^{AS} and H^{SA} embed the phase-transformation activation conditions in eq. 2.4 and they are defined by the relations:

$$H^{AS} = \begin{cases} 1 \text{ if} \begin{cases} R_s^{AS} < F < R_f^{AS} \\ \dot{F} > 0 \end{cases} \\ 0 \text{ otherwise} \end{cases}$$

$$H^{SA} = \begin{cases} 1 \text{ if} \begin{cases} R_f^{SA} < F < R_s^{SA} \\ \dot{F} < 0 \end{cases} \\ 0 \text{ otherwise} \end{cases}$$

$$R_s^{AS} = \left[\sigma_s^{AS}\left(\sqrt{\tfrac{2}{3}} + \alpha\right)\right], \quad R_s^{SA} = \left[\sigma_s^{SA}\left(\sqrt{\tfrac{2}{3}} + \alpha\right)\right]$$

Due to advent of computers, any complex physical model can be converted to a suitable mathematical model to test the leanness of the product design. In the current dissertation, numerical analysis for crystallographic studies, macroscopic and micro-macro mechanics studies needs to be constructed. The model being built on the statistical mechanics-ensemble average [9] strain energy method [10], the equations are most likely to be non-linear indeterministic continuously infinitely differentiable equations. Utmost applications of these alloys in biomedical industries, Finite Element Analysis (FEA) was mostly relevant to these specifications. Few such works are [11] for medical purposes, actuator designs [12], damping devices [13] etc. As the technology has shown an exponential growth, simulation environment made compatible to solve problems from molecular level to macro level. In this pretext, simulations were performed to understand the local thermo elastic material behavior upon loading [14], pure bending of ideal psuedoelastic SMA beams [15], numerical simulation to study structural morphing [16], stability analysis of cantilever beam [17], cohesive zone model to estimate the crack growth in SMA [18] as shown in Figure 1.

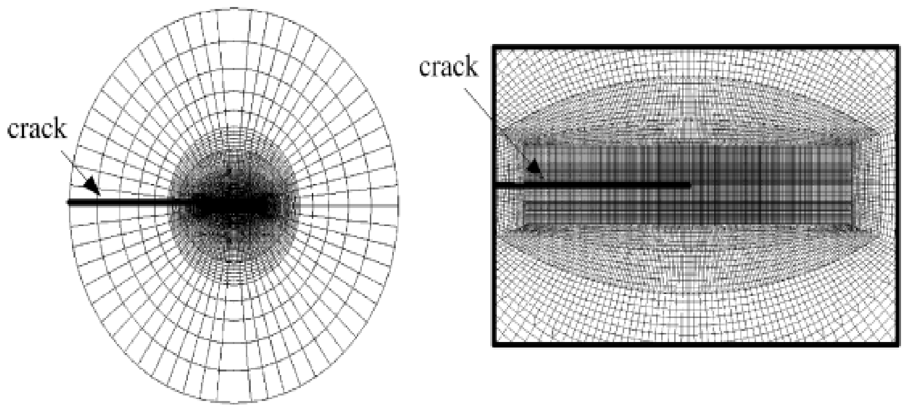

Figure 1: (a) The Finite Element Mesh used in the Analyses with 21,260 4-Noded Isoparametric Elements and 124 Linear 4-Noded Interface Elements. (b) The Crack Tip Region.

A nonlinear FEA method is developed to study aero-thermal characteristics of these alloys in [19], adaptive wing development [20] as shown in Figure 2.

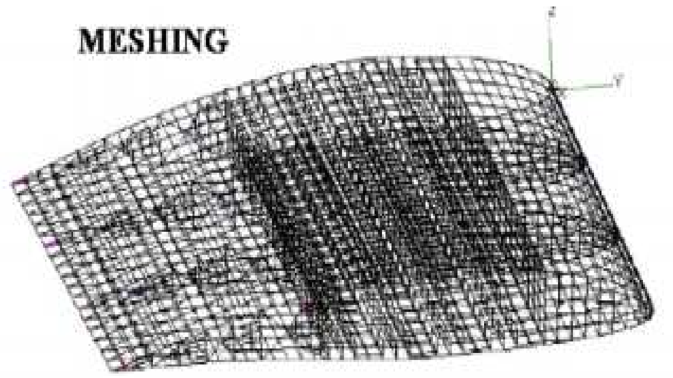

Figure Error! No text of specified style in document.**: Flexible Wing-Rib for Camber Control, SMA Torsion Tubes and Meshing of the Structure.**

An FEA model to predict the yielding due to Mode III fracture of shape memory alloys [21] as shown in Figure 3. Though model has few limitations such as mechanisms involved in unloading conditions and influence of multiple loading conditions, it has captured enough parameters to estimate the mechanics of zone in martensite with plastic deformation.

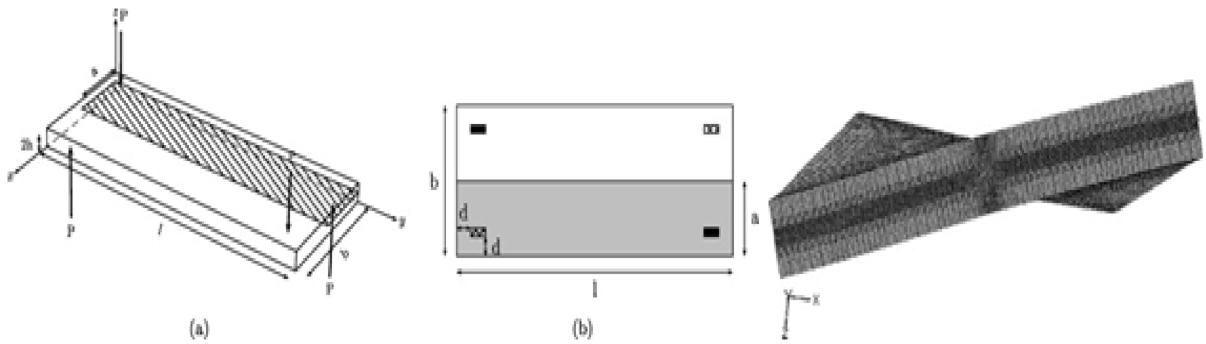

Figure 3: Nitinol SMA Strip-(a) Isometric View and (b) Top View (Before Deformation) and Complete Right Hand Side Represents Meshed Deformed Body.

FEA user defined material (UMAT) was developed based on the finite strain phenomological model on a helical spring to see the compactness of the constitutive mechanics established for Nitinol alloys [22] which can be seen in Figure 4. The paper account one of the important observation is that, it improved efficiency in computing fourth-order tensors. The same rheological model has been verified by [23] considering an elastic beam.

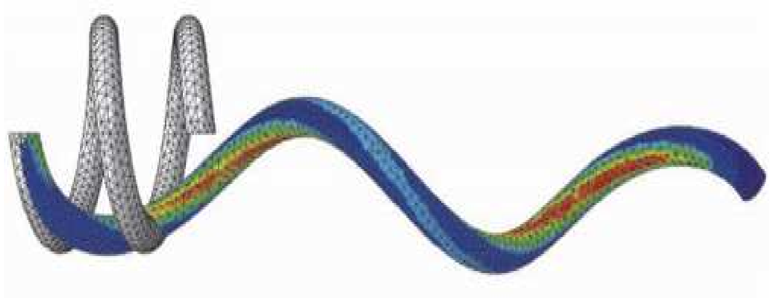

Figure 4: Pseudo-Elastic Spring: Comparison of Initial Geometry and Deformed Configuration.

For the first time, the phenomological model developed analytically by [24] was applied numerically and validated experimentally by [25] for the SMA helical spring as shown in Figure 5.

Due to substantial research available in the literature, it can be observed from all these models, there is no such effective constitutive model which can solve problems related to various industries even though it is same material i.e., Nitinol SMA. This is because of its unstable behavior, here unstable behavior prefaces to alloy composition, processing parameters and manufacturing route/environment rendering to diverse behaviors. Hence, in the present work we would use numerical methods to validate our model by performing series of numerical analysis by choosing an appropriate product design.

Figure 5: SMA Spring (Left-Experimental) and (Right-Numerical).

Physical body simulations with a numerical framework can be analyzed in a GUI environment using ANSYS software. ANSYS stands for Analysis Systems developed by Swanson as a framework working on the principle of Finite Element Analysis (FEA). As the solution meets the nearest approximation, computational time and data storage requires larger thus realizing the model compactness to a physical body problem. In our present context, an attempt is made to realize the stress-strain-temperature hysteresis without considering the atomistic effects. However, the latest versions of the software enhanced its tools by allotting a provision for user-defined inputs. In the current context, to meet the objectives, we are designing an actuator spring which is subjected to static structural (Super elasticity) and thermal loading (SME).

3. PROBLEM STATEMENT

From the literature review, it can be observed that existing models could not include precise parameters which effect the trend of the physical property of SME's using numerical simulation. To surmount and include these parameters into a numerical simulation, shall be addressed in the present work. This will be enveloped in the form of an FEA model which should envisage the compactness and compatibility of the model applicability and suggest the adjustable parameters which are required to intrude into the software model from the outputs observed from the FEA analysis. This is estimated to suggest additional parameters which could make a change in outcome of the numerical simulation of SMA's.

4. METHODOLOGY

4.1 Numerical Analysis

Initially we developed a Shape Memory Actuator and analyzed it numerically using Finite Element Analysis (FEA) package by giving essential properties shown in Table 1 obtained from [26] parameters for various loading conditions and temperatures. A series of loading conditions have been considered as it is difficult to find out the phase transition

temperatures and yield strength of the material. Now, for various values of loading parameters, the stress-strain curves and phase diagrams were calibrated to analyze the phase transition temperature and yield strengths of the material from the curves. Henceforth the values of these results for each trial have been plotted and are compared with the constitutive model and proposed model to validate it and find the exact values of the input parameters.

Table 1: Properties of Nitinol

Property	Value
Density	6.45 gm/cm^-3
Coefficient of thermal expansion	1.1E-05 C^-1
Young's Modulus	60000 MPa
Poisson's Ratio	0.36
Hardening Parameter	1000 MPa
Reference Temperature	223 K
Elastic Limit	50 MPa
Temperature Scaling Parameter	2.1 MPaK^-1
Maximum Transformation Strain	0.04
Martensite Modulus	45000 MPa
Lode Dependency Parameter	0.05

4.2 Proposed Model

The shape matrix of the specimen as a function of different stages which is one of the supplementary to our work will be discussed. Following reference pattern is used to define different stages of the specimen exhibiting SME.

Stage 1: As received specimen (shape functionS_{ro})

Stage 2: Stress induced deformation (S_{dd})

Stage 3: Stress Free State (S_{rd})

Stage 4: Stress free reference temperature (S_{dr})

Stage 5: Strain induced transformation temperature (S_{tt})

Stage 6: Strain recovery at reference temperature (S_{or})

The tensor matrix representation of the coordinates in above Figure is given below.

$$S_m = \begin{bmatrix} C_1 & S_{ro} & S_{dd} \\ S_{or} & C_2 & S_{rd} \\ S_{tt} & S_{dr} & C_3 \end{bmatrix} \qquad 6$$

The eigenvectors of the eq.6 for each process will give the respective shape of the specimen in the process. An eigenvectors for S_{ro} will be solved and the other process can be solved similarly. Eigen values of the equation 6 is given as

$$e_{ro,1} = C_3, \qquad e_{ro,2,3} = \frac{(C_1 + C_2) \pm \sqrt{(C_1 - C_2)^2 - 4S_{or}^2}}{2} \qquad 7$$

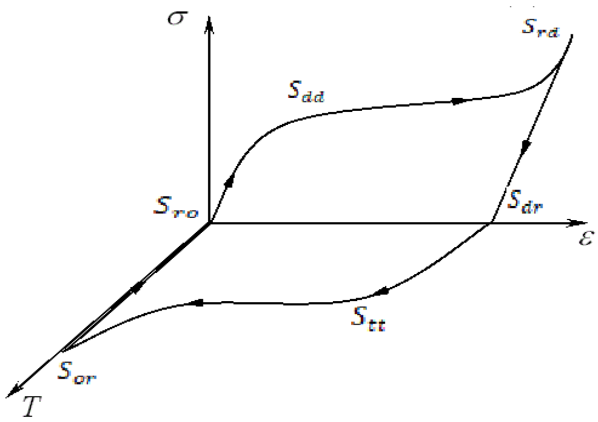

Figure 6: Shape Recovery Matrix (Representation of Shape Coordinates).

It can be clearly understood from the equation 7 that eigen value are combination of real and complex conjugates. Simultaneously, the real part of the conjugate pair is observed to be positive and this clears the ambiguity of state of the system indicating specimen can never come back to its equilibrium i.e., specimen in the phase is in metastable state. This indicates that stress induced first order maternsitic phase transformation takes place at very low stress. Hence the eigenvectors correspond to the shape of the specimen. Where C_1 and C_2 are the adjustable coefficients. The results associated with the suitability of proposed model will be discussed in the next paper. The following results and discussions will helps to derive the inputs and amenability of the proposed model.

5. RESULTS AND DISCUSSIONS

The stress-strain and strain-temperature curves in Figure 7 are obtained for the circular shaft which exactly shows the shape memory effect with the parameter values shown in Table 1. Since for any component of the trend, the axial load predicts the linear trend because of the model parameters and constitutive relations between these parameters. As a result, no family of curve can be observed in the Figure 7 below retrieved from Table 2 and Table 3. It is also indicative that the stress-strain-temperature curve as shown in the Figure 6 is similar but a straight line trend.

5.1 Output

Table 2: Stress and Strain Data

strain	0	1.98E-06	3.96E-06	6.94E-06	8.28E-06	9.09E-06	3.33E-05	3.33E-05
stress	0	3.35E+07	6.71E+07	1.17E+08	1.40E+08	1.54E+08	1.72E+08	0.00E+00

Table 3: Strain-Temperature Data

T	22	22.1	22.2	22.3	22.4	22.5	22.6	22.7	22.8	22.9	23	23.1	23.2	23.3	23.4	23.41
ε	3.33E-05	3.07E-05	2.79E-05	2.33E-05	2.09E-05	1.84E-05	1.62E-05	1.37E-05	1.13E-05	9.26E-06	6.97E-06	5.34E-06	3.83E-06	2.09E-06	3.73E-07	-4.52E-09

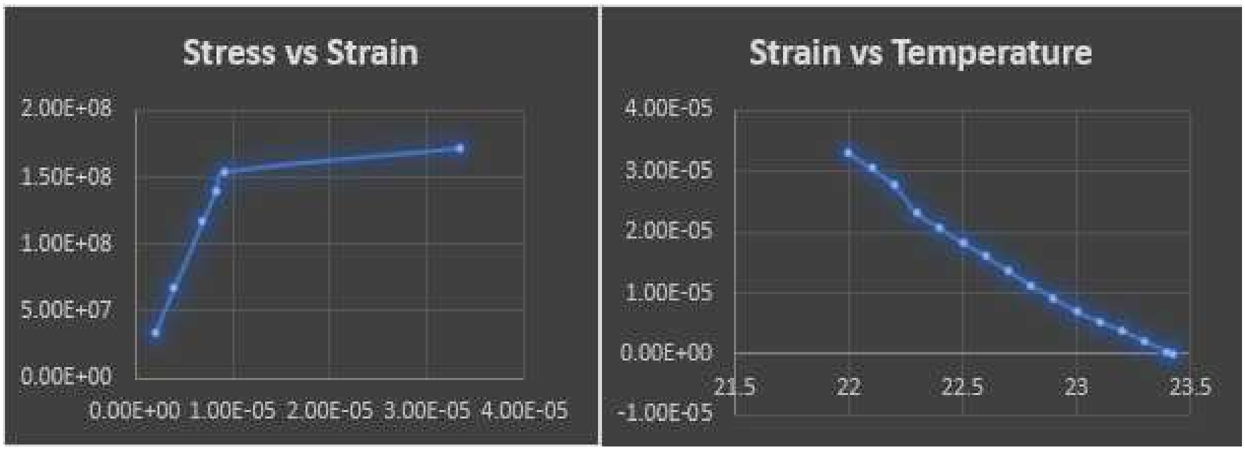

Figure 7: Graphs Developed Using Circular Shaft.

The graphs of stress-strain and strain-temperature curves in Figure 9 with the parameter values as in Table 1 on the spring of the shape memory actuator as shown in Figure 8 are obtained as below. The loading parameters with respect to shape memory actuator have been suggesting the variation of stress-strain-temperature curve with a modularity indicating the change in load carrying capacity. It is also imperative that the curves are obtained from rigorous iterations but unable to predict the composition. This drawback is addressed as shape recovery in the present proposed model.

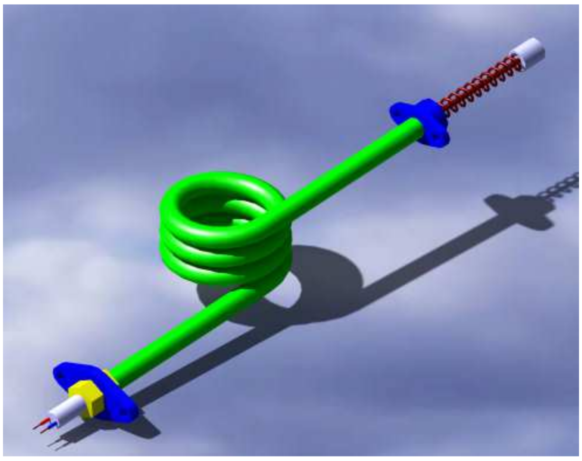

Figure 8: Shape Memory Actuator.

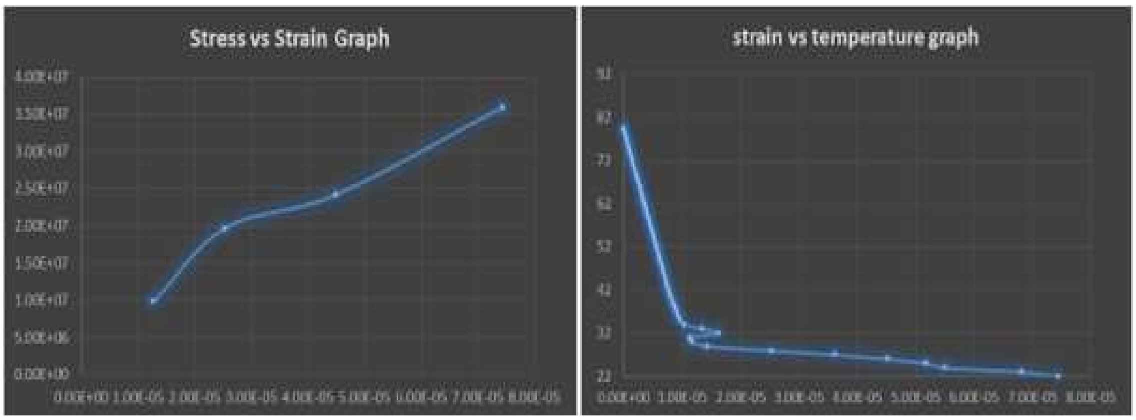

Figure 9: Graphs Developed Using Spring of Actuator.

6. CONCLUSIONS

Comparison of these graphs show that the trend of the stress-strain curves and strain-temperature curves of Shape Memory Effect (SME) are different for different loading conditions. Thus making it difficult to understand the first order martensitic phase transformation followed by the transition temperatures and yield strengths of the material. Apart from this, the results also suggest more predefined information on material atomistic characteristics composition of the materials is required. However existing constitutive models cannot predict the atomistic behavior of the alloy and hence we preferred numerical simulations. But numerical simulations have a quandary to model the number of parameters which requires filtering of data to match the experimental data. As a result the expected outcome enabled to propose a model which is realized from the statistical data obtained from numerical simulation.

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